Dynamics and Simulation of Extreme and High Impact Weather Events over India

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Submitted by

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1. Title

Dynamics and Simulation of Extreme and High Impact Weather Events over India

2. Summary of the thesis

2.1 Background

One of the extreme and high impact weather events in South Asian winter is heavy fog, which may extend over tens to thousands of kilometres and lasts for several days. It is well known that fog and low cloud affect marine transport and aviation, as a reduction in visibility affects both the safety and efficiency of air-traffic management (Allan *et al*., 2001). Fog reduces visibility which results in accidents and also affects human health. The total economic loss associated with the impact of fog occurrence can be comparable to that of tornadoes or, in some cases, winter storms and hurricanes (Gultepe et al. 2007). Improved prediction of low-visibility events is valuable in safety and economic terms, for example in reducing fuel and diversion costs to airlines (Leigh, 1995).

The international definition of fog consists of a collection of suspended water droplets or ice crystals near the Earth's surface that lead to a reduction of horizontal visibility below 1 km (5/8 of a statute mile; National Oceanic and Atmospheric Administration, (NOAA), 1995). If the visibility is greater than 1 km, then it is called mist (WMO, 1966). The main mechanism is radiative cooling, but the opposing influences of upward soil heat flux, as well as warming effects and moisture losses through dew deposition and from turbulent mixing in the stable boundary layer largely determine the likelihood and timing of radiation fog formation (Roach et al. 1976; Turton and Brown 1987; Fitzjarrald and Lala 1989; Duynkerke 1999).

Over northern India, most of the fog formation is due to radiative cooling but, advection fog has also been observed (Dutta 2010). Radiation fog usually forms near the surface under clear skies in stagnant air in association with an anticyclone (Gultepe et al. 2007). Fog in Delhi (28˚35'N; 77˚12'E, 218 m asl) is a persistent winter phenomenon; the peak months of dense and persistent fog are December and January. Both its inland position and the prevalence of continental air influence the climate of Delhi; the winter period (December–February) is dominated by cold, dry air and ground–based inversions with low wind conditions. Because of the radiational cooling at night during the winter season, fog in Delhi can be classified as radiation fog (Pasricha et. al., 2003; Choudhury et al. 2007).

Fog prediction presents a formidable challenge to Numerical Weather Prediction (NWP) models due to its often small spatial and temporal scales. The formation, dispersion, and decay of fog are the result of complex interactions among microphysical, thermodynamical, and dynamical

processes. The research on fog, with comprehensive model development and dedicated measurements fields campaigns, has been active since the 1970s; Gultepe et al. (2007). Numerous field studies with a focus on fog and other boundary layer clouds were performed over the last few decades. Application of one-dimensional models for fog simulations, despite ignoring horizontal heterogeneities, provides many insights into fog physics. For example, Zdunkowski and Nielsen (1969) and Brown and Roach (1976) showed the importance of radiative cooling at the fog top on surface layer destabilization and on downward propagation of the fog. Brown (1980) and Mason (1982) investigated the effect of radiative cooling on droplet growth and modification of the droplet spectrum. Modeling by Musson-Genon (1987) emphasized the importance of turbulence in fog formation and evolution. Bott et al. (1990) and Bott (1991) studied effects of aerosol activation and composition on fog droplet distribution and visibility. Duynkerke (1991) showed that vegetation and its type strongly influence fog formation by changing the surface heat and moisture budget. An investigation of low-level stratus/fog was performed by Koracin et al. (2001) using a one-dimensional (1-D) model and observations with results suggesting that radiative cooling and large-scale subsidence was an important factor for fog formation. The interactions between radiative and turbulence processes studied in detail by Oliver et al. (1977; 1978) suggested that radiative cooling at fog top was an important process in the fog life cycle. Radiation fog studies using detailed surface observations were lead by Meyer et al. (1986) and Choularton et al. (1981). These authors had also focused on various aspects of fog formation and its evolution by using numerical models.

A major challenge is to develop models that embody the various processes related to fog to generate skillful forecasts. However, for effective applications such forecasts should have sufficient accuracy in parameters like time of onset, intensity and duration. Similarly, it is important to identify the critical values and meteorological conditions for formations and dissipation of various types of fogs under different large-scale conditions.

2.2 Objective and scope of the work

The present thesis describes the development of an analogue dynamical model which is an alternative and practical post processing model in an attempt to improve the fog prediction. The present thesis quantifies the differences among key meteorological variables in the context of foggy and non-foggy days. The analogue dynamical model has been used to forecasts visibility (proxy for fog) over Delhi; the validation has been carried out against hourly observations provided by Indian Meteorological Department (IMD), India. The basic analogue dynamical model of fog has been interfaced with observed meteorological variables from COMoN (Climate Observation and Modeling Network) data to evaluate potential and skill of the model for forecasting visibility at different temporal scales (hourly, daily and monthly). The model is also evaluated by interfacing with forecasts generated by atmospheric meso-scale model like Weather

Research and Forecasting (WRF). The impact of large-scale weather variables on fog is also presented in the thesis. Chapter-wise outline of the thesis is provided below.

2.2.1 Chapter 1 Introduction

This chapter begins with the brief description of the characteristics and mechanism of formation of fog over India as well as other parts of the world. This chapter also provides the overview of the work present in the thesis.

2.2.2 Chapter 2 Data and methodology

The chapter 2 presents the description of the general data sources (surface and upper air observations) and forecast configuration and validation of an atmospheric meso-scale model WRF. We have also described the basic equations to compute the composite structure of various meteorological variables for foggy and non-foggy days. Specific data and methodology are described in the related chapters.

2.2.3 Chapter 3 Quantification of observed local characteristics: contrasts in foggy and non-foggy days

Fog is a quasi-continuous process that depends on certain thresholds and regimes of the meteorological variables. For example, winds stronger than a given threshold can disrupt fog formation through turbulence (Zhou and Ferrier 2008); at the same time, complete absence of wind can inhibit fog formation due to lack of mixing (Rodhe1962; Welch et al. 1986). Similar conditions are also applicable for relative humidity and temperature (Meyer et al. 1990). Due to the prevailing background conditions and local processes, the differences are likely to be site-specific and season-specific. In particular, the meteorological fields are expected to be different for foggy and non-foggy days; an important requirement, therefore, is to identify and quantify the differences in the meteorological variables for foggy and non-foggy days. This chapter quantifies the differences among key meteorological variables in the context of foggy and non-foggy days. Quantification of these differences for a given location can help to assess, validate and configure meteorological forecast model for driving fog prediction. However, a quantification of the contrasts in the meteorological fields for foggy and non-foggy days is essentially missing. We examine this question over Delhi, a fog prone metropolis, with observed data from different sources.

2.2.4 Chapter 4 Simulated contrasts for foggy and non-foggy days: assessment of forecast skill of a meso-scale model WRF

An observational analysis over Delhi city (28˚35'N; 77˚12'E, 218 m asl) has shown that temperature, relative humidity, dew depression (difference between temperature and dew-point temperature) and wind speed show significant differences between foggy and non-foggy days. The contrasts revealed in various fields at different levels for foggy and non-foggy days indicate the precision and the accuracy required in simulation of the meteorological fields for forecasting fog; smaller contrast in a field means that a model requires more accurate prediction of this field. However, such conditions or forecasts of the fields themselves do not necessarily imply acceptable skill in the forecasts of the contrasts. An important requirement, therefore, is to validate meteorological forecasts in terms of these contrasts. This chapter presents such a validation of an atmospheric meso-scale model (Weather Research and Forecasting; WRF) over a fog-prone metropolis (Delhi). While we consider validation of the forecasts of the variables themselves in terms of standard measures, the focus is on simulating and validating the forecasts in terms of the observed contrasts in the meteorological fields for foggy and non-foggy

2.2.5 Chapter 5 Forecasting of radiation fog: Formulation of analogue dynamical fog model

This chapter introduces a dynamical fog forecast system with a new algorithm for computation of fog (visibility) driven by meteorological fields from observations and forecasts. Here we focus on the megacity Delhi (28.38 N, 77.12 E). Delhi, the capital of India, is characterized by a high frequency of fog events (De et al., 2005; Jenamani 2007). There are only few specific studies (Mohan et al., 2009; Mitra et al., 2008; Saraf et al., 2010) over India, for fog simulation and prediction. Here the model is presented as an analogue model that represents key processes of fog; however, the emphasis is on the forecast skill and not on basic physics of fog.

2.2.6 Chapter 6 Forecast Strategy: Model Calibration, Validation, Forecast skill and Evaluation Parameters

This chapter describes the performance of the analogue fog forecast model is evaluated by comparing with benchmark (perfect) and test forecasts. The benchmark simulations have been generated by driving the analogue fog model with observed hourly meteorological fields from COMoN. The test forecasts of fog (visibility) are generated by driving the analogue fog model with meteorological forecasts from an atmospheric limited area model (Weather Research and Forecasting; WRF). The purpose of the benchmark (perfect) simulation is to create a reference set of simulations against which the prediction of visibility driven by the atmospheric meso-scale

forecasts, with a lead time of 24 hours, can be tested. The validation is carried out against hourly observed values for visibility recorded at Indira Gandhi International Airport (IGIA); Delhi in terms of distribution of errors in visibility. A number of parameters like average error in visibility, fog onset and duration, bias, Hit rate, False warnings were used to quantify the skill of the forecasts.

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2.2.7 Chapter 7 Sensitivity Analysis

Most of the parameters used in the analogue fog model are based on calibration, it is necessary to examine the sensitivity of the results of these parameters. While this requires a very large number of experiments, we discuss here few cases to highlight certain important points. The calibration process, in effect, is an optimization process. Thus sensitivity analysis also allows us to examine other configurations, within the uncertainties of the semi-empirical constants.

2.2.8 Chapter 8 Impact of large-scale weather variables on fog frequency variability

The spatio-temporal characteristics in fog frequency were investigated by Syed et. al., (2012) using observational station data over south Asian region. They found significant increasing trends in the fog frequencies (FF). Gradual increasing trends were also found in specific and relative humidity over the region which is highly correlated with observed and detected fog. This chapter examines the relationships of FF to the changes in large –scale atmospheric circulation and to reveal some causes and potential changes to fog occurrence during winter (December-January; DJ).

2.2.9 Chapter 9 Conclusions and future scope

This chapter includes a summary of the entire study and the major findings. This chapter also discusses some of the limitations and potential improvements of the model.

3. Brief descriptions of the thesis chapters

3.1Quantification of observed local characteristics: contrasts in foggy and non-foggy days

3.1.1 Introduction

Our main objective is to investigate and quantify contrasts in meteorological variables for foggy and non-foggy days. We have examined this question for three winter seasons (December-January; 2009-2012) over a fog prone metropolis, Delhi, with different data sets; fog has been

quantified in terms of visibility on non-rainy days. Quantification of these differences for a given location can help to assess, validate and configure meteorological forecast model for driving fog prediction. However, a quantification of the contrasts in the meteorological fields for foggy and non-foggy days is essentially missing. We examine this question over Delhi, a fog prone metropolis, with observed data from different sources.

3.1.2 Results

Our results revealed consistent contrasts in the meteorological variables of temperature, humidity, dew point temperature and wind for foggy and non-foggy days. For all the cases the contrasts are noticeably higher for dense fog than those for mild fog days. While large contrasts are seen for individual years, the differences are smaller but persistent when averaged over the years; this is expected, especially since the foggy days do not have the same hour of onset and duration.

A scrutiny of hourly distributions of 2m air temperature, relative humidity, dew-depression (difference between temperature and dew-point temperature, and wind speed revealed contrasts in foggy and non-foggy days. Again the contrast is more evident for days with dense fog than for mild fog days. Several important features are revealed by an examination of the observed vertical profiles of the four meteorological variables for foggy and non-foggy days. For December season during 2009-2011 (Figure 1) and for January season from 2010-2012 (Figure 2), the composite vertical profiles of temperature from observation for foggy and non-foggy days show distinct characteristics. In terms of near surface temperature, the average contrast for the month of December is 1.1°C for mild fog cases whereas it is 2.4°C for dense fog cases (Table 1); however, for January the average contrast is lower (1.3°C for dense fog). The contrast in temperature for foggy and non-foggy days decreases at 850 mb level for both December and January (Table 2).

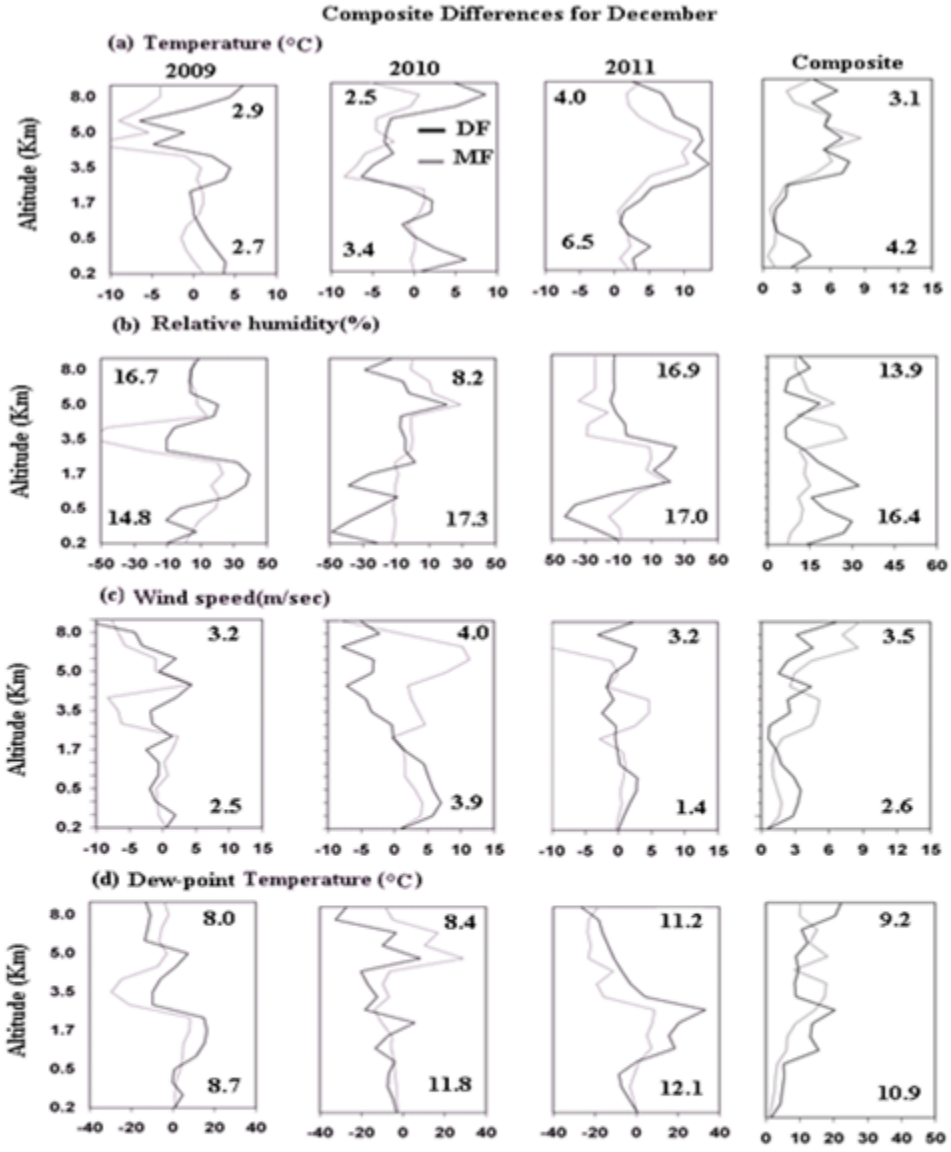

Figure 1 Differences between composites of vertical profiles of non-foggy days and moderate fog days (MF, solid grey lines) as well as dense fog days (DF, solid black lines) of duration ≥ 4 hours for temperature (panel a), relative humidity (panel b), wind speed (panel c) and dew-point temperature (panel d) during the month of December through 2009-2011. The numbers in the panels denote the absolute difference between composites of vertical profile for MF (top) and DF (bottom) cases.

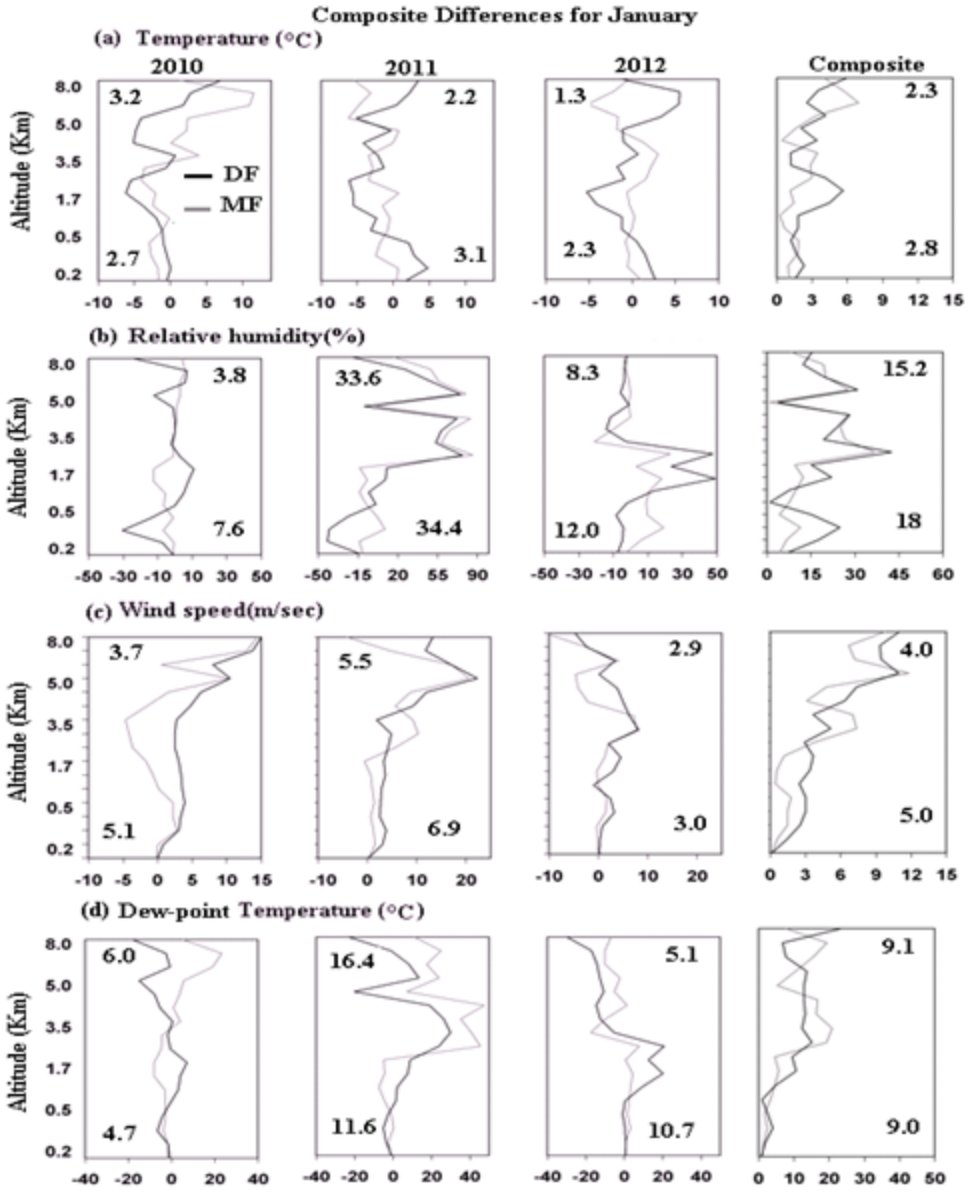

Figure 2 Differences between composites of vertical profiles of non-foggy days and moderate fog days (MF, solid grey lines) as well as dense fog days (DF, solid black lines) of duration ≥ 4 hours for temperature (panel a), relative humidity (panel b), wind speed (panel c) and dew-point temperature (panel d) during the month of January through 2010-2012. The numbers in the panels denote the absolute difference between composites of vertical profile for MF (top) and DF (bottom) cases.

Table 1 Summary of contrasts in composites of observed meteorological variables at near surface over Delhi during December 2009-2011 and January 2010-2012 for moderate fog cases (MF), dense fog cases (DF) of duration ≥ 4 hours and non-fog cases (NF). Observed values are based on radiosonde observations at 00 UTC from Safdurjang airport, Delhi.

Period	T (°C)			RH (%)			W (m/s)			T_d (°C)		
	MF	DF	NF	MF	DF	NF	MF	DF	NF	MF	DF	NF
Dec-2009	10.5	8.1	11.7	81.0	92.5	82.0	0.0	0.0	0.6	7.3	7.0	8.7
Jan-2010	10.4	9.2	8.7	85.0	86.0	85.0	0.1	0.1	0.0	7.9	6.9	6.3
Dec-2010	9.4	8.6	9.4	87.0	95.6	75.4	0.3	0.1	1.1	7.3	7.9	5.2
Jan-2011	7.5	6.2	8.0	86.0	89.2	75.7	0.4	0.5	0.7	5.3	4.5	3.9
Dec-2011	9.7	8.8	11.8	81.0	83.0	73.0	0.3	0.0	0.0	6.6	5.9	7.1
Jan-2012	9.1	7.5	10.1	85.0	90.7	83.0	0.2	0.0	0.2	6.7	6.1	7.3
Dec-Average	9.8	8.5	10.9	83.0	90.3	76.8	0.2	0.0	0.2	7.2	6.9	7.0
Jan-Average	9.0	7.6	8.9	85.3	88.6	81.2	0.2	0.2	0.3	6.6	5.8	5.8

Table 2 Summary of contrasts in composites of observed meteorological variables at 850 mb pressure level over Delhi during December 2009-2011 and January 2010-2012 for moderate fog cases (MF), dense fog cases (DF) of duration ≥ 4 hours and non-fog cases (NF). Observed values are based on radiosonde observations at 00 UTC from Safdurjang airport, Delhi.

Period	T (°C)			RH (%)			W (m/s)			T_d (°C)		
	MF	DF	NF	MF	DF	NF	MF	DF	NF	MF	DF	NF
Dec-2009	9.8	10.5	11.7	38.2	17.5	64.7	5.9	6.6	6.0	-3.8	-13.5	-4.1
Jan-2010	11.5	13.4	8.7	24.3	14.0	19	7.2	7.2	7.3	-8.2	-13.6	-11.4
Dec-2010	9.5	8.2	10.2	25	53.3	14.6	6.2	3.4	7.8	-9.5	-1.1	-15.6
Jan-2011	9.2	11.0	8.7	30.4	22.2	16.9	7.4	5.6	8.5	-7.3	-13.2	-15.1
Dec-2011	10.6	9.8	10.2	24	20.6	42.1	5.8	6.6	6.9	-9.1	-19.4	-1.2
Jan-2012	6.3	9.4	8.7	39.8	37.2	50.8	6.4	7.3	6.3	-6.3	-11.9	-3.2
Dec-Average	9.9	9.5	10.6	29	30.4	40.4	5.9	5.5	6.9	-7.4	-11.3	-4.2
Jan-Average	9.0	11.2	8.8	31.5	24.4	28.9	7.0	6.7	7.3	-7.2	-12.9	-9.9

3.2 Simulated contrasts for foggy and non-foggy days: assessment of forecast skill of a meso-scale model WRF

3.2.1 Introduction

The meso-scale forecasts have been tested for their ability to distinguish between foggy and non-foggy days for all the three important variables: wind, humidity and temperature. The simulated contrasts are compared against the corresponding observed values; independent data sets were used wherever possible. The contrasts were also examined in terms of spatial distributions of meteorological variables in and around Delhi.

3.2.2 Results

A summary of skill in the simulation by WRF shows comparable error with respect to respective observations. The 24-hour model forecasts are very sensitive to the initial conditions. In terms of near surface temperature, SC for dense fog cases (Fig. 3, top right panel) is stronger than that of mild fog cases (Fig.3, top left panel). The contrast in temperature for both SC and OC decreases at 850 mb level for mild (Fig. 4.4, top left panel) cases, while it increases for dense (Fig. 4, top right panel) fog. The time average of observed and simulated near surface humidity for both December and January shows discernible contrasts (~ 5%) for all the six fog seasons for mild fog (Fig. 3, middle left panel); whereas for dense fog cases (Fig. 3, middle right panel) the contrast is about 10% for both SC and OC, indicating dense fog days are more wetter than mild fog days. However, both SC and OC are much higher (> 10%) for 850-mb relative humidity (Fig. 4, middle panels). Wind can play a significant role in the dynamics of fog through ventilation. Both SC and OC in the near surface wind for both mild fog (Fig. 3, bottom left panel) and dense fog (Fig. 3, bottom right panel) showed appreciable and consistent differences, including in upper level winds (Fig. 4, bottom right panel); although in general the contrasts are not very strong (~ 1.5 m/s) for both observed and simulation (Fig. 3), they are persistent over all the years. In particular, the dense fog days were found to be characterized by large vertical shear in general.

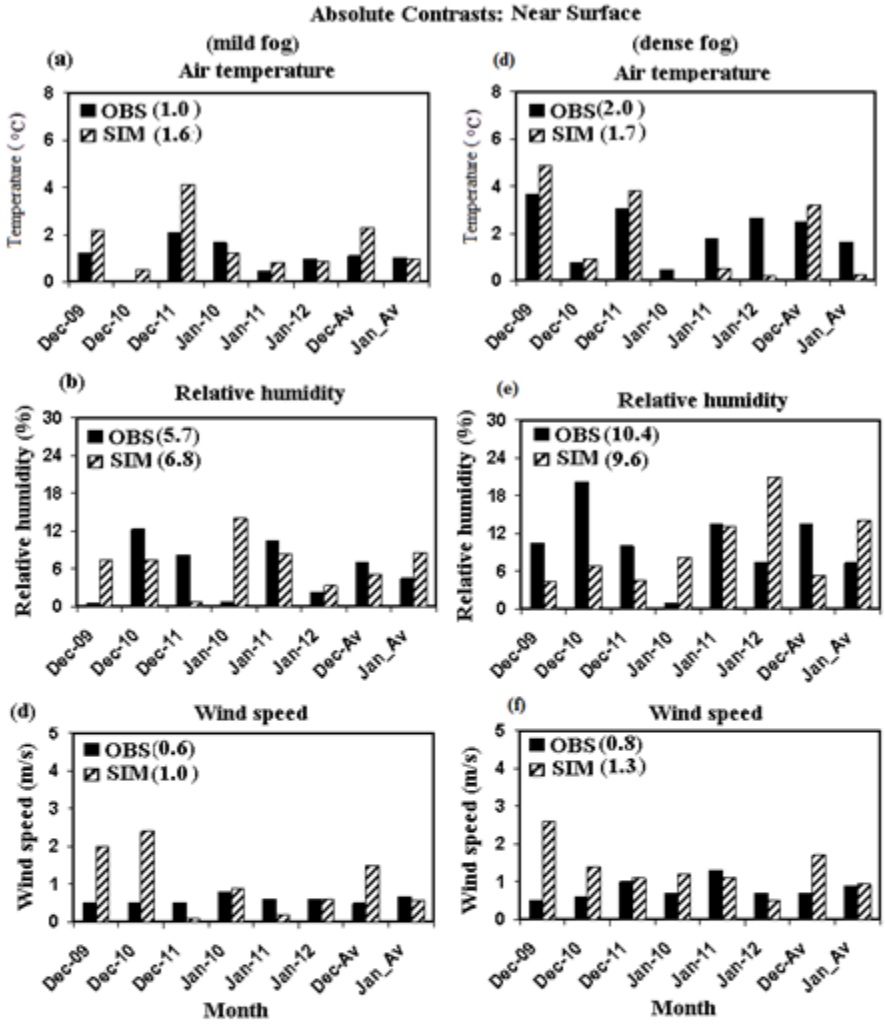

Figure 3 Monthly averages of observed (black bars) and simulated (shaded bars) absolute contrasts in air temperature (°C; panels a,d), relative humidity (%; panels b,e) and wind speed (m/s; panels c,f) between composites of non-foggy days and mild fog days (left panels) and dense fog days (right panels) at near surface. Observed meteorological variable is adopted from radiosonde observation at 00 UTC over Delhi Safdurjang airport for the months December and January through 2009-2012. Simulated variable is adopted from area averaged forecasts around Delhi from an atmospheric meso-scale model WRF for the same period. The numbers in the bracket are the average contrasts for observed and simulated cases for the respective variables.

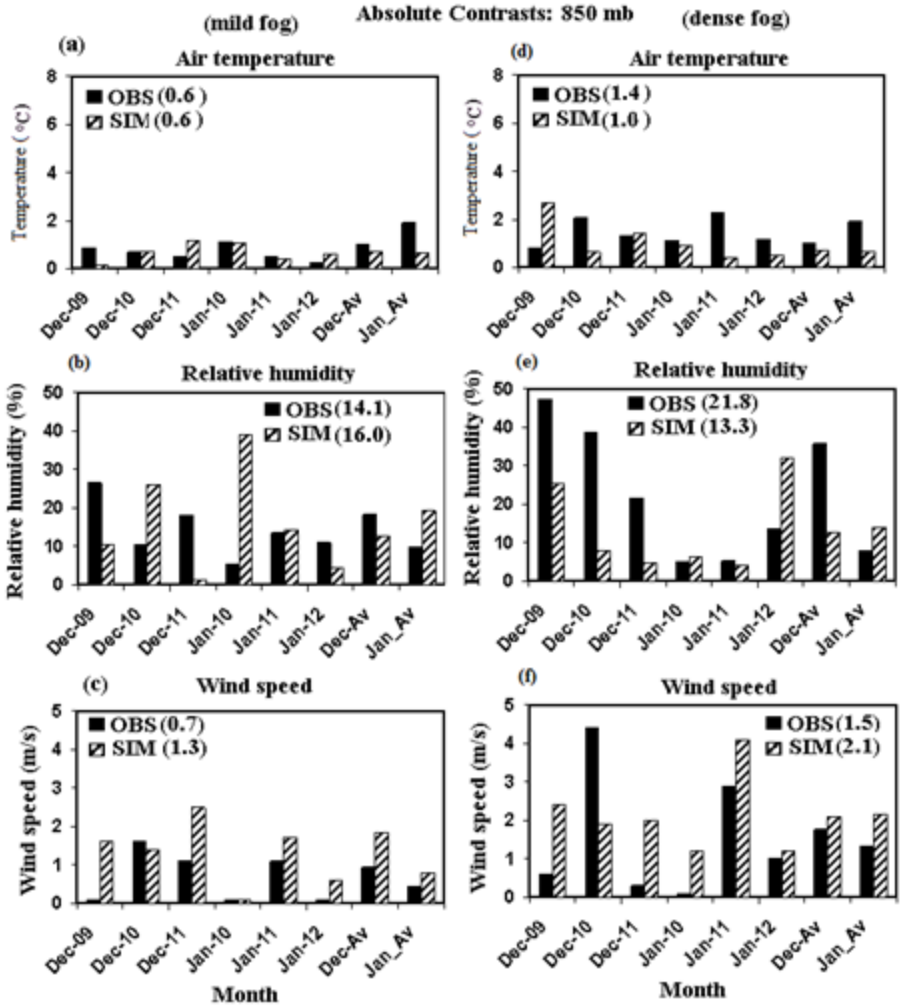

Figure 4 Monthly averages of observed (black bars) and simulated (shaded bars) absolute contrasts in air temperature (°C; panels a, d), relative humidity (%; panels b, e) and wind speed (m/s; panels c, f) between composites of non-foggy days and mild fog days (left panels) and dense fog days (right panels) at 850 mb pressure level. Observed meteorological variable is adopted from radiosonde observation at 00 UTC over Delhi Safdurjang airport for the months December and January through 2009-2012. Simulated variable is adopted from area averaged forecasts around Delhi from an atmospheric meso-scale model WRF for the same period. The numbers in the bracket are the average contrasts for observed and simulated cases for the respective variables. respective variables.

3.3. Formulation of analogue dynamical fog (visibility) model

Based on the physical and dynamical considerations; the analogue model has been formulated as the combination of genesis, persistence and dissipation mechanisms of fog leading to change in visibility. The reduction in visibility due to formation of fog depends not only on water content but the ambient environmental condition. We use visibility with reference to clear sky (V_R) as a measure of fog (V_F); thus the reference visibility is reduced due to fog as expressed by the following expression,

$$V = V_R - \alpha V_F \quad (1)$$

α= Visibility reduction coefficient

Following convention, we adopt a value of 1000 meters for the reference (clear sky) visibility (V_R). The dynamics of fog at hourly scale is represented as

$$\frac{dV_F}{dt} = F_G + F_P - F_D \quad (2)$$

The term on the left hand side represents time variation of intensity of fog represented by a proxy like visibility (such as a result of the number of cloud droplets at a point). The terms F_G, F_P and F_D represent, respectively, the processes that trigger, maintain and dissipate fog, also varying in time. A primary requirement for formation of fog is also the availability of adequate cloud condensation nuclei (CCN). However, for an urban environment like the Delhi air basin it can be assumed that adequate amount of CCN is always present in the atmosphere (Goswami *et al*., 2008; Goswami *et al*., 2011; Srivastava et al., 2012). Thus the dynamics of fog is considered to be essentially controlled by the meteorological conditions. The initial condition is given as the observed visibility.

3.3.1 The genesis process

The term F_G is comprised of parameters reflecting the state of local meteorological conditions. It is a nonlinear term which implicitly incorporates the synchronous processes leading to fog formation. It is expressed as,

$$F_G = F_q * F_T * F_{Ts} * F_w * F_{rad} \quad (3)$$

Where, F_q, F_T, F_{TS}, F_w *and* F_{rad} represents respectively the dependency on near surface relative humidity, air temperature, soil temperature, wind speed and net radiation respectively. The

multiplicative nature of the terms in equation (3) represents the necessity of each atmospheric variable to fulfill certain conditions.

3.3.2 The persistence process

The persistence of the steady stage implies that there exists a certain self-sustenance mechanism or a balance in its liquid water budget. In general, it is a complex process and depends on the presence of fog itself in a non-linear manner, to bring about the self-regulation. In our model the simple representation of non-linear self-sustained persistence term given as

$$F_P = \alpha_p * F * F \quad (4)$$

Where, α_P = fog persistence constant or self-regulating parameter and F is fog of previous hour.

3.3.3 The dissipation process

We thus represent the dissipation process as a function of near surface wind and the solar heating and are given by

$$F_D = \alpha_D * w \quad (5)$$

Where α_D is fog dissipation constant

3.4. Forecast skill in visibility: Model Evaluation with meteorological variables from COMoN and WRF model

The monthly average diurnal cycles of observed visibility over IGI airport (dark bars, Figure 5) shows generally low visibility in the early hours of local time both in December (Figure 7, left panels) and January (Figure 5, right panels); however the reduction in visibility is much stronger in January. The benchmark forecasts (shaded bars, Figure 5) capture these trends well in general, with correlation coefficients between observed and benchmark forecasts above 99% level of significance in all but one case (December, 2011); with meso-scale forecasts (crossed bars, Figure 5), the correlation between observations and forecasts is generally significant at about 95% level.

Comparison of forecasts of foggy days of mild (daily visibility < 1000 meter) and dense (daily visibility < 500 meter) for the six winter seasons shows (Figure 6) that the analogue fog model driven by the meteorological fields from WRF forecasts can accurately represent the observations. Histogram of errors shows about 60% of the benchmark forecasts to be within

error of 100 meters; for meso-scale forecasts, about 50% of the forecasts are in the error bin of 100 meters (Figure 7). It is worth noting that for the both months the distributions of forecasts in the error bins are nearly Gaussian (Figure 7); it is also worth noting that for both months, the % of benchmark forecasts with large errors (500 meters) is only about 0-5%.

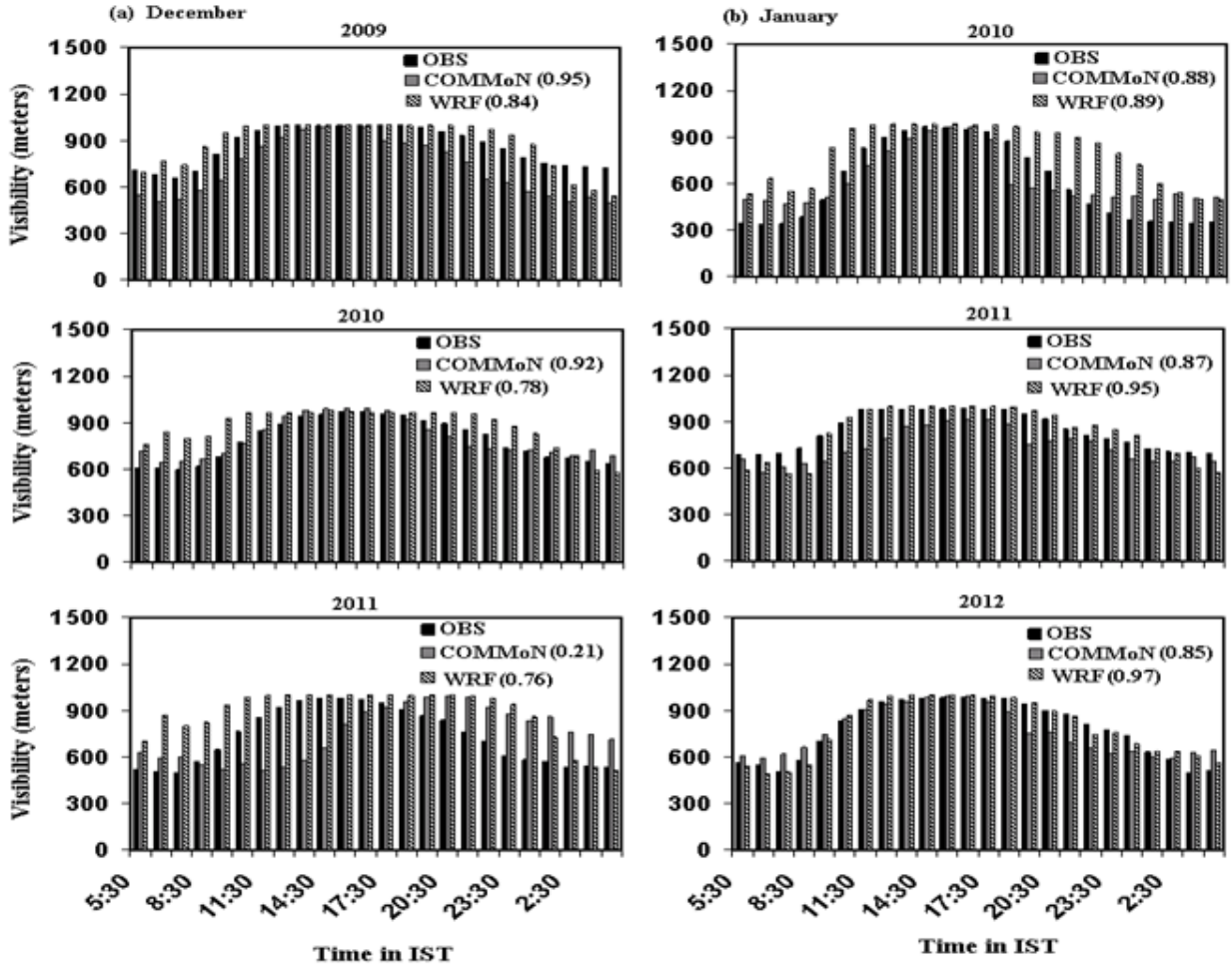

Figure 5 : Diurnal distribution of monthly averaged visibility from observation (black bar) and simulation with COMoN data (grey bars) and simulation with WRF forecast (shaded bar) over IGI Airport, Delhi during the winter months (a) December 2009-2011(the left panels) and (b) January 2010-2012 (the right panels). The numbers in the bracket represent CC between hourly observed and simulated visibility for the respective cases. The 99% (95%) significance of correlation is 0.5 (0.4).

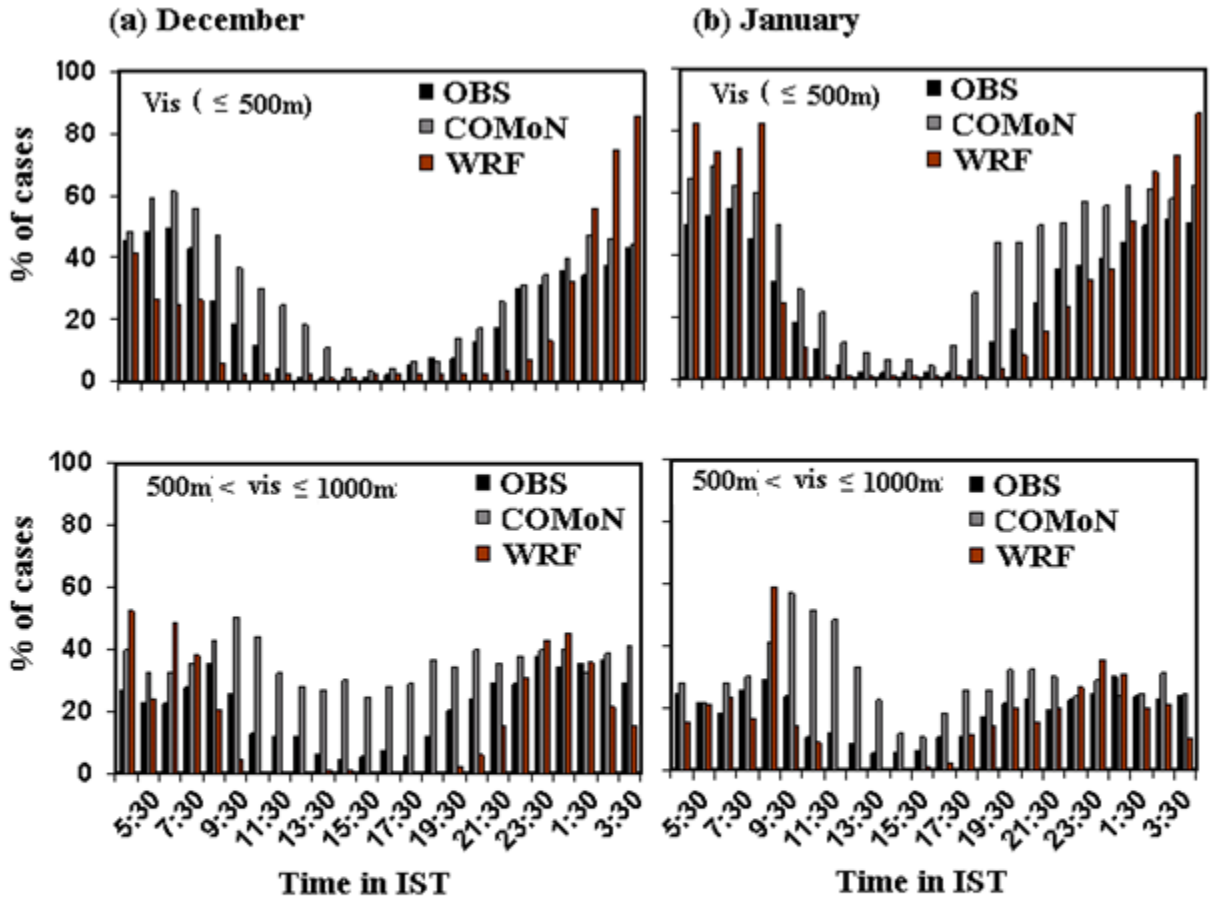

Figure 6 Frequency distribution of average % of dense fog (visibility ≤500m) and mild fog (500m < visibility ≤ 1000m) cases as a function of time of a day from analogue fog model driven by COMoN data (grey bar) and by forecast from WRF (color bar). The black bars denote the observed values. The computation has been done for December (left panels) through 2009-2011 and that of January (right panels) during 2010-2012.

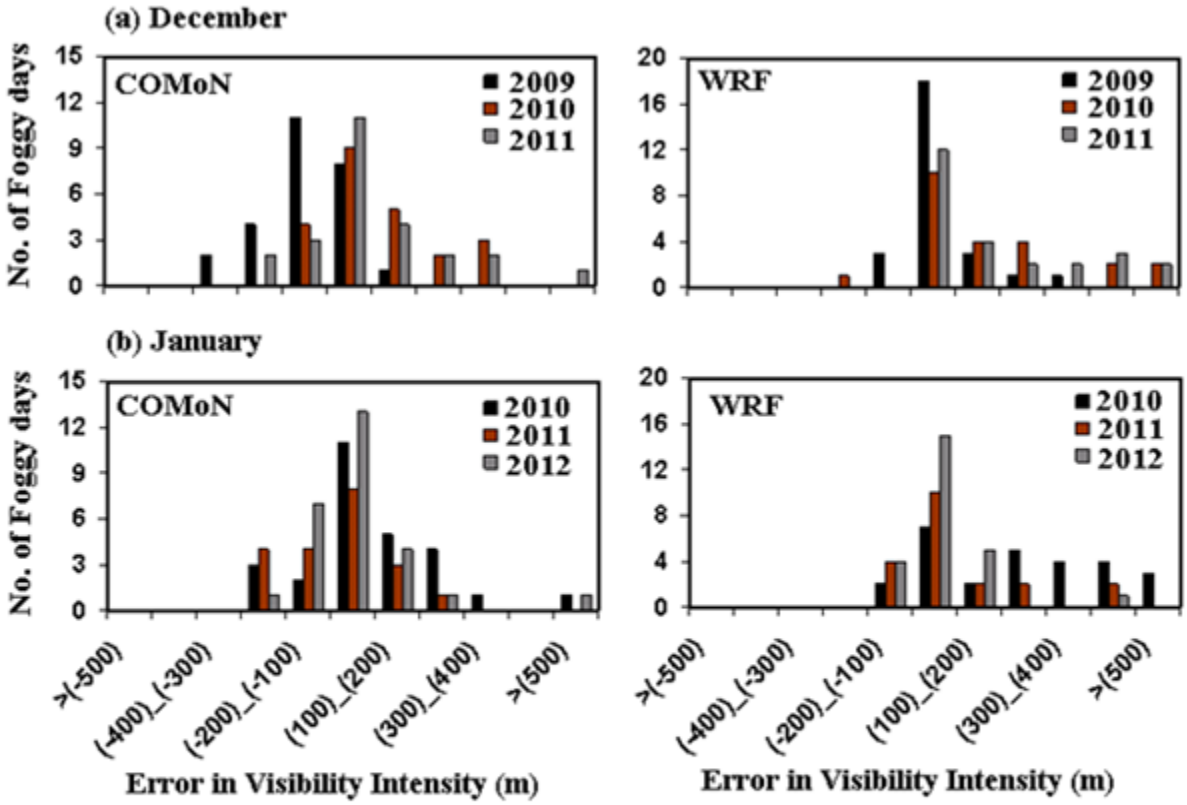

Figure 7 Histogram of errors in visibility intensity showing the number of foggy days in different error bins (predicted -observed) for benchmark simulation (COMoN) and for test forecast (WRF) for the months of December (upper row) and January (lower row) through 2009-2012.

3.5 Sensitivity Analysis

3.5.1 Introduction

Because of the sensitivity of the forecasts to various uncertainties in prescribing the semi-empirical parameters, it is important to examine and quantify the variations in the forecasts due to changes in some of the parameters. In this chapter we have investigated the sensitivity of the forecast skill of the analogue fog model to the uncertainty in the input parameters and to the spatial variations of both the observed meteorological fields (multisite evaluation) as well as interpolated fields from WRF model.

3.5.2 Results

In order to get more insight of the variability of the forecast skill of the analogue fog model due to the variations in the model parameters; we have conducted two series of sensitivity tests by varying the threshold value in dew-depression, relative humidity and fog-constant as follows,

1st Case Exp1: Dew-depression (°C) =2.5, RH (%) = 60, Fog-constant = 1.15

2nd Case Exp2: Dew-depression (°C) =1.7, RH (%) = 45, Fog-constant = 0.62

The results have been discussed in terms of diurnal distribution of monthly average forecasted visibility for December 2010 and January 2011. Figure 8 shows that the sensitivity analyses with the new set of parameters have produced comparable results for the ANL_WRF; the correlation coefficients are all comparable and there is not much impact on the overall trends of the observed diurnal variations. Whereas, for ANL_COMoN the set of parameters used in the second case (Exp2) of sensitivity analysis; cannot capture the observed diurnal variations.

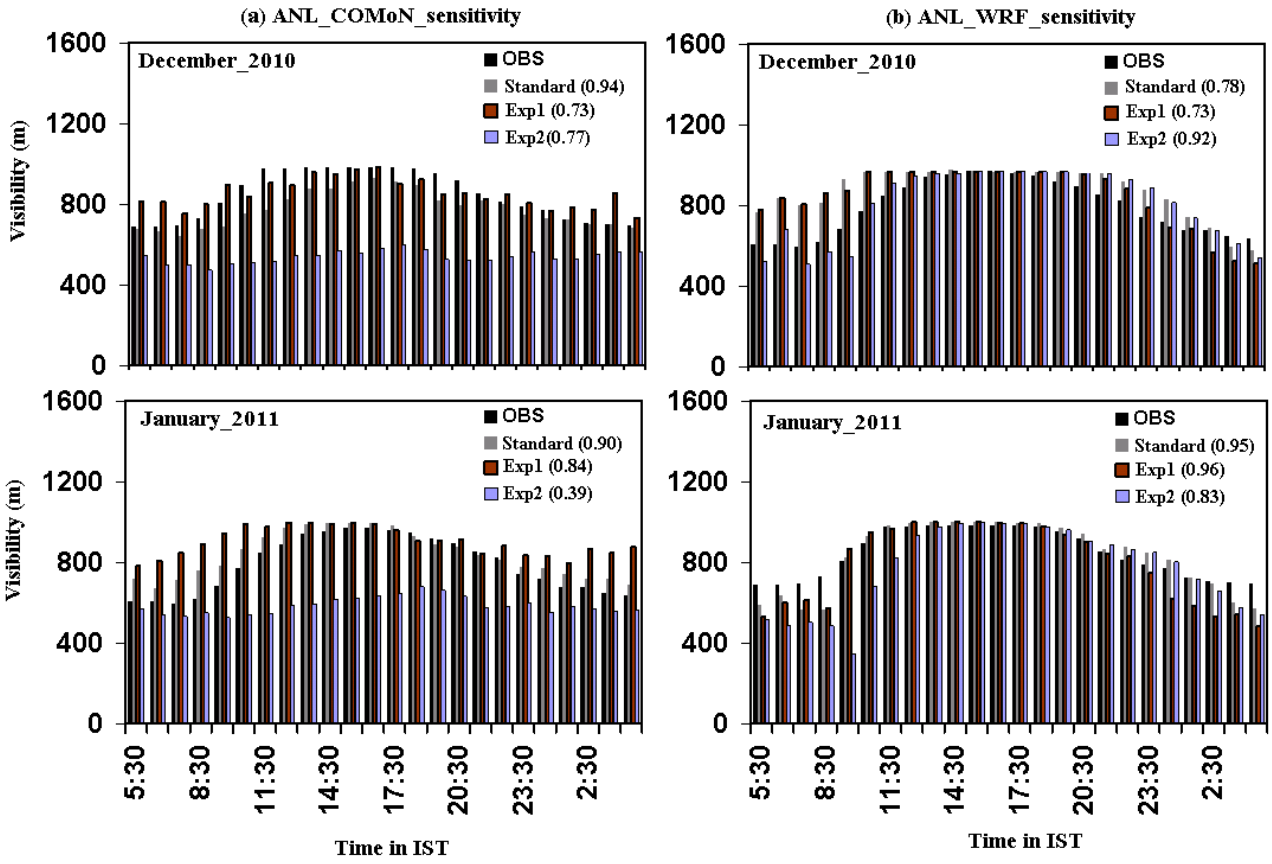

Figure 8 Sensitivity analyses in terms of diurnal distribution of monthly averaged visibility from observation (black bar), and simulation with analogue model (standard case, grey bars ; Exp1, red bars ; Exp2, blue bars) with COMoN ((a),left panels) and with WRF forecasts ((b), right panels) over IGI Airport, Delhi during the winter months December-January through 2010-2011. The numbers in the bracket represent CC between hourly observed and simulated visibility for the respective cases. The 99% (95%) significance of correlation is 0.5 (0.4).

We have generated the spatial variation in the WRF forecasts fields by averaging over the model grid cells. The horizontal resolution of the innermost domain is about 4x4km^2. We have selected a relatively coarser domain of 100x100 km^2 for averaging. We have summarized the impact of low resolution meso-scale fields on the forecast skill in terms of average error, false warnings, over warnings and misses in the Table 3. Figure 9 shows a comparison of the analogue fog model driven by low resolution meteorological fields to that of test forecasts (ANL_WRF) in

terms of distribution of error histograms of visibility intensity for the winter 2010-11. It may be seen that there is no significant change in the error histogram by using low-resolution fields from WRF. However, there is a subtle increase in the dailiy average error in visibility intensity (Table 3) due to the increase in percentage of false warnings. It is evident from these analyses that fog forecast skill of the ANL_WRF is not significantly modified, showing that the ability of WRF meso-scale model to reproduce meteorological conditions leading to fog formation is not significantly reduced by spatial averaging even if the averaging is done over hundreds of kilometers.

Parameters	2010-11	
	ANL_WRF	ANL_WRF (low-res)
Mean absolute error in daily average visibility (e_A) (m)	154.95	161.24
Percentage of false warning days (P_{FW})	9.65	19.3
Percentage of misses (P_M)	6.4	9.6
Percentage of over warning days (P_{OW})	0.0	0.0
Days with average error (>300 m)	9	10

Table 3 Summary of performance of the ANL_WRF by using low-resolution meteorological fields from WRF for the Winter (December 2010-January 2011).

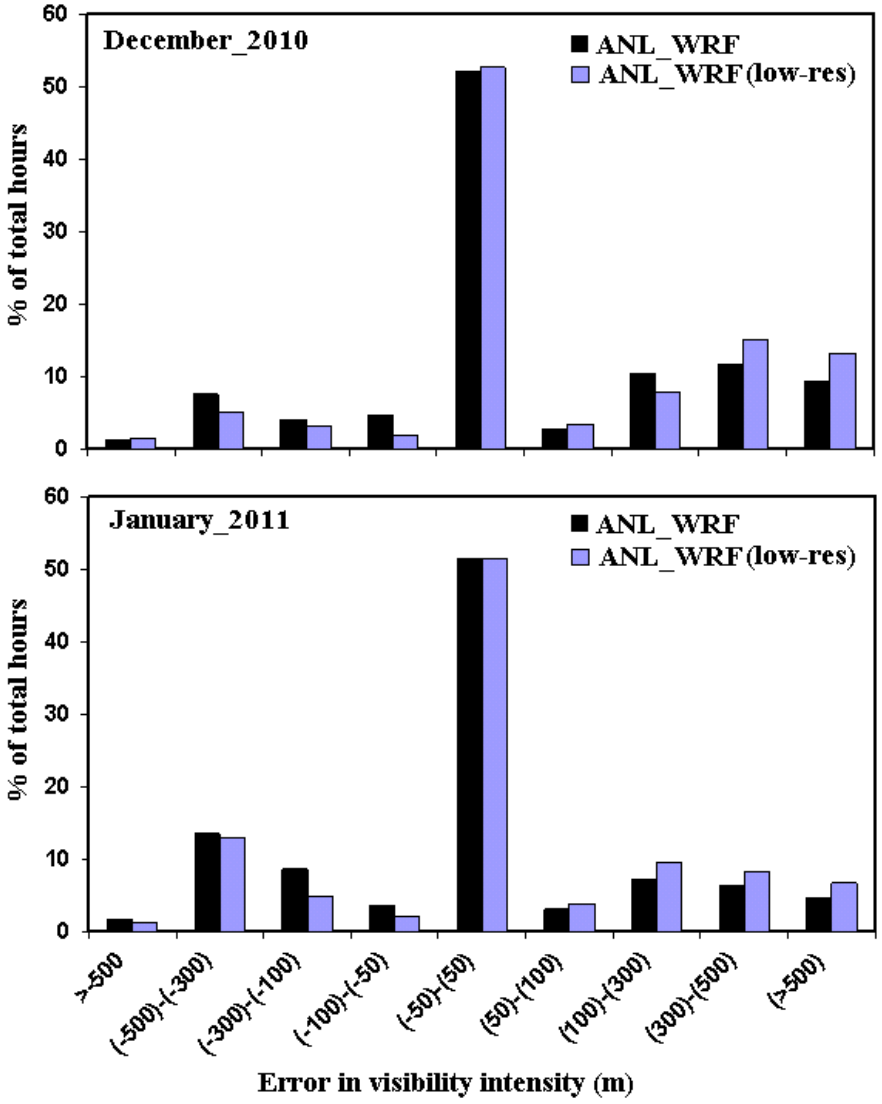

Figure 9 Histogram of errors in visibility intensity showing the total % of hours in different error bins (predicted -observed) for test forecast (ANL_WRF, black bar) and forecasts with low-resolution (ANL_WRF (low-res), color bar) for the months of December (upper row) and January (lower row) through 2010-2011.

3.6. Impact of large-scale weather variables on fog frequency variability

3.6.1 Relationship of winter FF and regional climate variability

To investigate the relationship between the winter FF and local atmospheric environmental changes in December and January, the inter-annual variations (Figure 10) in 500 geopotential height anomalies, meridional wind and wind divergence at 1000 mb, difference in specific humidity between 925 and 700 mb, difference in temperature and relative humidity between 850 and 700 mb and wind shear from 1000-850 mb level were examined across the IG plain for the period 1980-2012. These large-scale fields have been derived from NCEP with areal average (20°N- 35°N and 70°E- 92°E) across IG plain. Inter-annual FF series from the four stations are compared among themselves and found to be strongly correlated ($r \sim 0.7$), suggesting the importance of common response to synoptic-scale climate forcing.

3.6.2 Analysis of extreme fog anomalies

The winters of extreme fog anomalies are important for understanding the full scope of observed variability. Examining winters of extreme anomalies, we found that fog was present in 1998-99, a frequency 7.1 times greater than the 2000-01 minimum. A composite (Figure 11) of sea-level pressure (SLP) patterns for high (one standard deviation higher than climatological frequency) FF years and low (one standard deviation lower than climatological frequency) FF years reveal a shift in the spatial structure of the High pressure system (1025 hPa contour).

3.6.3 Synoptic-scale circulation controlling the fog-frequency variability

In order to analyze the atmospheric background fields corresponding to the high and low FF years occurred across IG plains, a composite analysis for the winter months (DJ) has been done to depict the distributions (Figure 12) of anomalous geopotential heights, air temperature, moisture condition and winds in the lower (1000 hPa, 850 hPa) and middle (500 hPa) troposphere respectively.

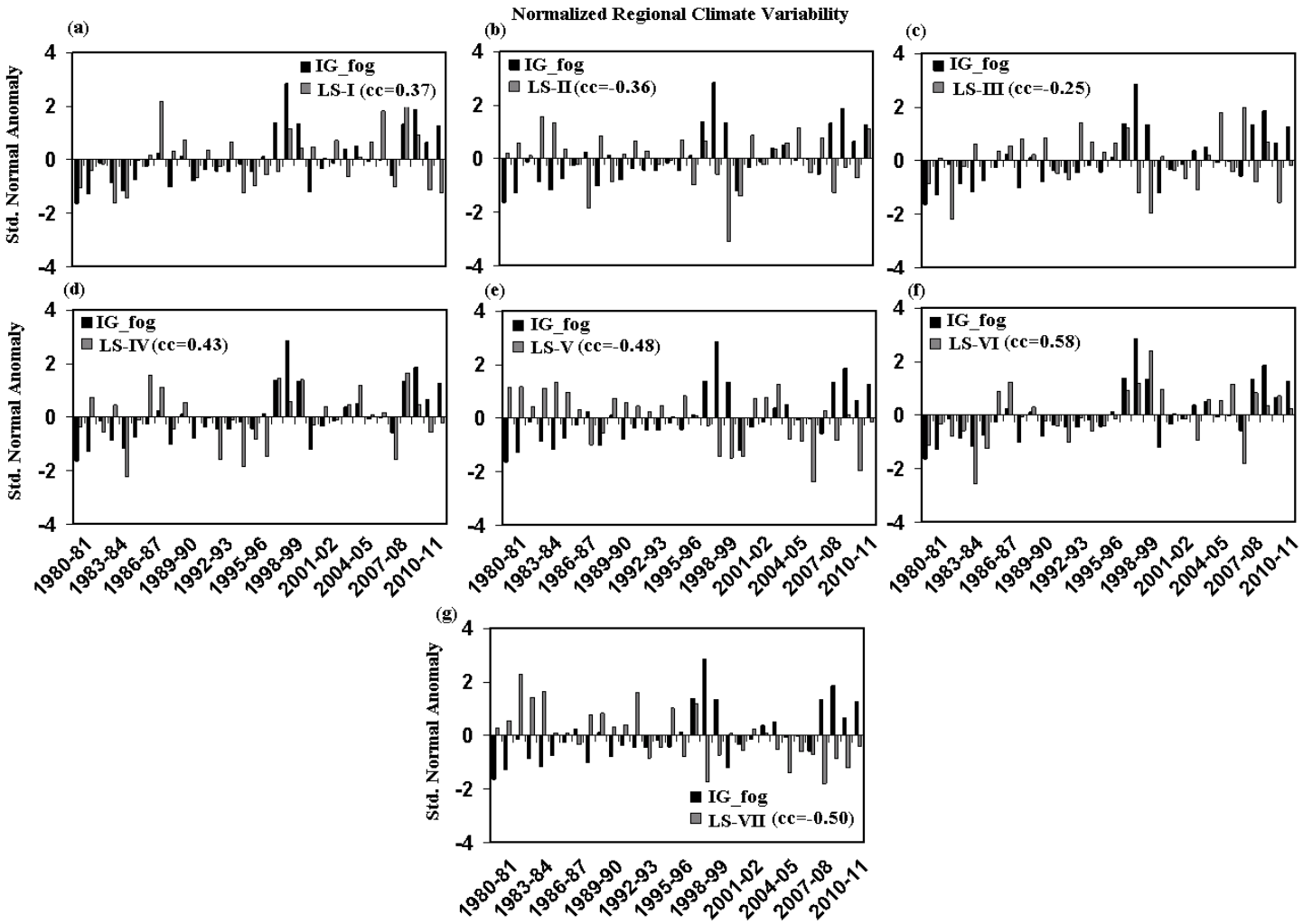

Figure 10 Inter-annual variability of winter time (December-January) IG fog frequency and other regional (averaged over 20°N- 35°N and 70°E- 92°E)climate variables from NCEP; plot includes: (a) 500 mb geopotential height anomaly(LS-I), (b) v-wind component at 1000 mb (LS-II), (c) wind divergence at 1000 mb(LS-III), (d) difference in specific humidity between 925 and 700 mb (LS-IV), (e) difference in temperature between 850 and 700 mb (LS-V), (f) difference in relative humidity between 850 and 700 mb (LS-VI) and wind shear from 1000 mb to 850 mb (LS-VII) during the period 1980-2012. All series normalized to zero mean and unit variance. The numbers inside the brackets represent correlation coefficient between IG fog frequency and the large scale variables for the respective cases. The 95% significance of correlation is 0.3

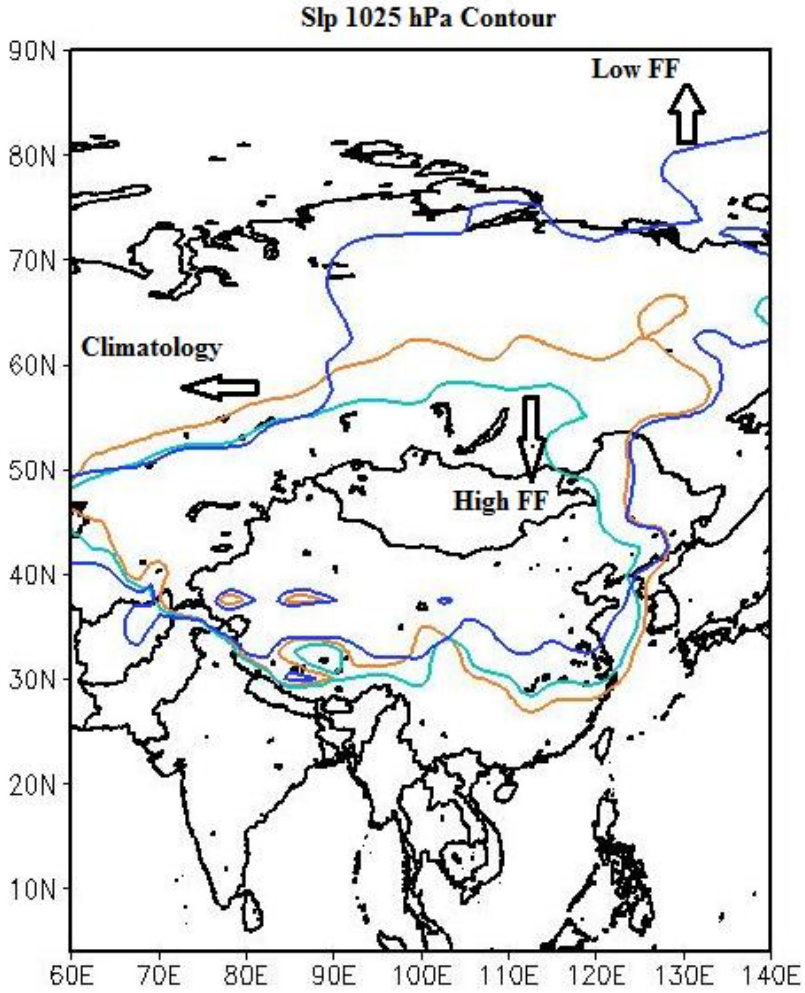

Figure 11 1025 hPa Isobar, illustrating Siberian High in the lowest fog frequency years (blue), highest fog frequency years (cyan blue) and its climatological (1980-2012) average (orange).

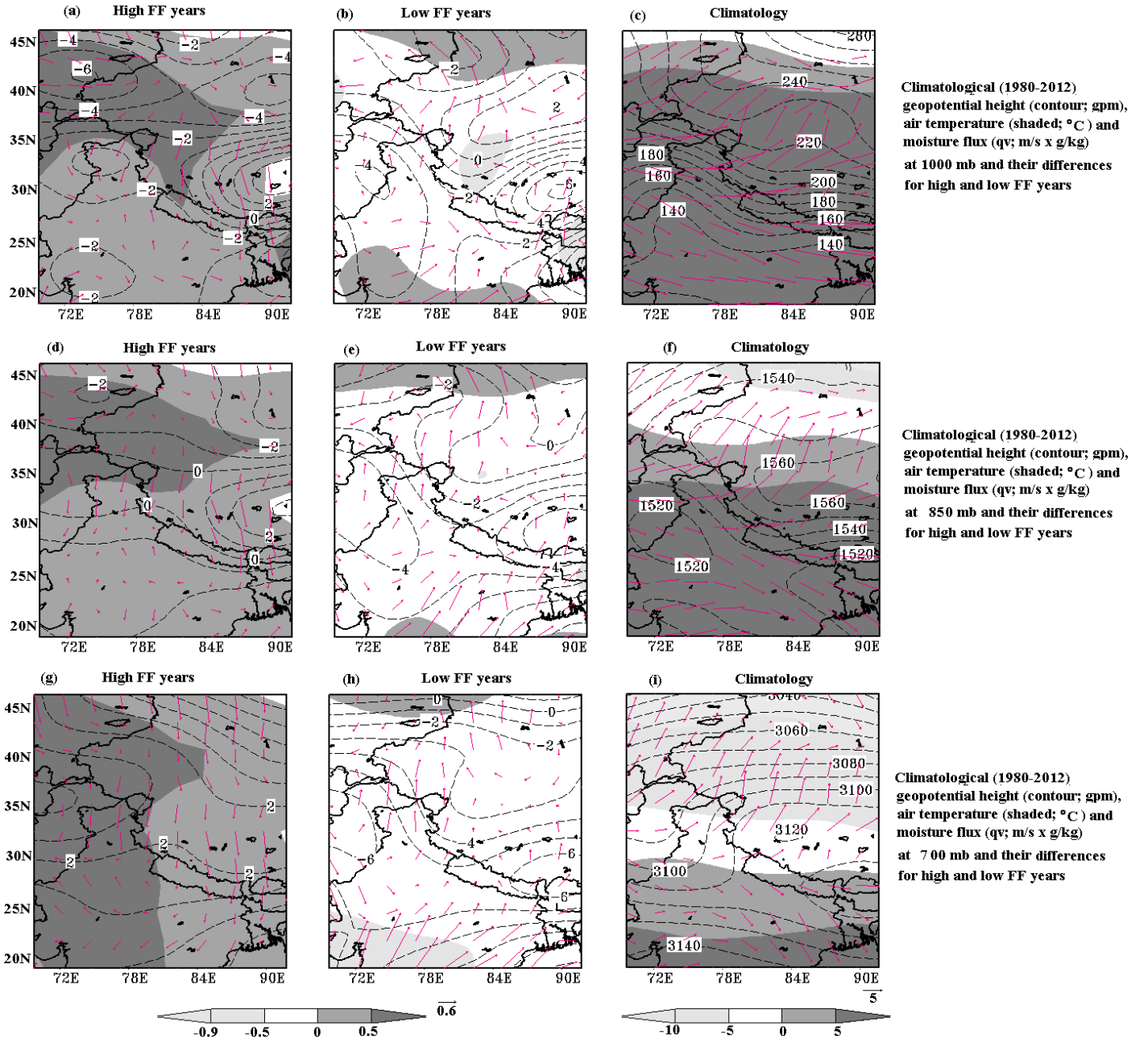
(a) High FF years
(b) Low FF years
(c) Climatology
(d) High FF years
(e) Low FF years
(f) Climatology
(g) High FF years
(h) Low FF years
(i) Climatology
45N
40N
35N
30N
25N
20N
72E
78E
84E
90E
Climatological (1980-2012) geopotential height (contour; gpm), air temperature (shaded; °C) and moisture flux (qv; m/s x g/kg) at 1000 mb and their differences for high and low FF years
Climatological (1980-2012) geopotential height (contour; gpm), air temperature (shaded; °C) and moisture flux (qv; m/s x g/kg) at 850 mb and their differences for high and low FF years
Climatological (1980-2012) geopotential height (contour; gpm), air temperature (shaded; °C) and moisture flux (qv; m/s x g/kg) at 7 00 mb and their differences for high and low FF years
-0.9
-0.5
0
0.5
0.6
-10
-5
0
5
5

Figure 12 Spatial distribution of winter time (December-January) climatological geo-potential height (contour ; gpm), air temperature (shaded, °C) and moisture flux (qv ; m/s) and the composite anomalies for high and low FF years for 1000 mb (upper panels), 850 mb (middle panels and 700 mb (bottom panels) level.

3.7 Conclusions and Future Direction

The objective of the present work has been to explore and evaluate the potential of a dynamical fog forecasting system with visibility calculated with observed meteorological fields (COMoN) for benchmark forecasts and from an atmospheric meso-scale model (WRF). As already emphasized, fog is a complex process and it is difficult to ascertain the completeness of a model; thus the merit of the model has to be assessed in terms of its forecast skill. The emphasis has been on generating skillful forecasts of fog-induced visibility rather than details of mechanism of fog formation. The validation of the forecasts against observations of visibility over Delhi airport for six winter months: December & January through 2009-2012, demonstrates significant skill in the forecasts in terms of a number of evaluation parameters. It is worth noting that the skill was found to be higher for dense (visibility < 500 meters) than for moderate fog. Thus the present model provides an applicable system for forecasting dense (visibility < 500 meters fog 24 hours in advance over Delhi. However, the methodology is quite generic and can be easily adopted for any location worldwide.

Fog needn't be only a diagnostic variable. However, fog cannot be, should not be, diagnosed from model output alone unless the model is refined to contain all the processes relevant for fog dynamics at appropriate accuracy and resolution. In most meso-scale atmospheric models, these processes of fog formation are not adequately represented. We are thus assuming a standalone fog forecast models driven by meteorological variables from observations as well as meteorological forecasts from an atmospheric model WRF.

It is true that improvements in the meteorological forecasts models are also necessary to improve fog forecasting. However, in parallel, we also need to improve prediction model for fog, a process that is not a part of all standard meteorological forecast models. In the formalism presented, the dynamics of fog is represented as having its own driving processes, some of which are driven by meteorological process. Our purpose is to highlight the fact that the dynamics of fog is determined by a number of parameters like land surface characteristics, non-linear process of dissipation and properly determined meteorological thresholds.

The present study also focuses on analysis of measurements of various meteorological fields between foggy and non-foggy days and tried to find their contrasts (differences). This work is

important in that fog is very sensitive to these fields. Contrast of any field, between foggy and non-foggy days, implies how sensitive of these fields to fog formation, development and dissipation are. The magnitude of contrasts of different fields at different levels implies the degree of sensitivities to fog for these fields at different levels. Smaller contrast in a field means that a model requires more accurate prediction of this field. This work shows temperature (T) and relative humidity (RH) have 1°C and 5-10 % contrasts, respectively near the ground. So T and RH require at least 1 degree and 5-10% precision to skillfully predict fog for a NWP model.

We have also examined the ability of WRF model in simulating the contrasts in basic regular meteorological variables (T, RH, and wind, dew-point depression) between fog (dense and mild) and non-fog days. The composite meso-scale structure of T, RH and wind for foggy and non-foggy days at different hours at near surface as well as 850 mb pressure level for the winter months December and January through 2009-2012 revealed characteristic meso-scale variability in these fields.

In the present study we have examined the skill of model performance over three consecutive winters (2009-2012). The contrasts for the different years do show appreciable differences; implying variability of the large-scale conditions from year to year, and their effect on fog occurrence over a location.

In the present work, the validation has been restricted to station observation (IGI airport), with the associated errors in downscaling. However, it is important to accurately simulate and forecast spatial variability in fog for applications in traffic and crop management. While it is now possible to generate forecasts at fairly high resolution using state-of-the-art meso-scale models and techniques like dynamical downscaling, a sufficiently dense observational network of visibility in fog prone areas with more frequent sampling is a critical requirement for model calibration and validation at high spatial resolution.

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List of Publications

1. Goswami, P., and Sarkar, S. (2015) Analysis and quantification of contrasts in observed meteorological fields for foggy and non-foggy days, Meteorology and Atmospheric Physics, 128(5): 605-623 Doi: 10.1007/s00703-015-0384-2.

2. Goswami P. and Sarkar S. (2016), An analogue dynamical model for forecasting fog - induced visibility: validation over Delhi, Meteorological Applications, DOI: 10.1002/met.1634.
(Acceptance letter from Journal editor has been attached).

3. Goswami P. and Sarkar S. (2016), An assessment of forecast skill of an atmospheric meso-scale model in simulating the observed contrasts in meteorological fields for foggy and non-foggy days, revised version is submitted to Pure and Applied Geophysics (Under Review).

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